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Correlation and trend studies of the sea-ice cover and surface temperatures in the Arctic

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ABSTRACT. Co-registered and continuous satellite data of sea-ice concentrations and surface ice temperatures from 1981 to 2000 are analyzed to evaluate relationships between these two critical climate parameters and what they reveal in tandem about the changing Arctic environment. During the 19 year period, the Arctic ice extent and actual ice area are shown to be declining at a rate of $-2.0 \pm 0.3\%\ \mathrm{dec}^{-1}$ and $-3.1 \pm 0.4\%\ \mathrm{dec}^{-1}$, respectively, while the surface ice temperature has been increasing at $0.4 \pm 0.2\ \mathrm{K\ dec}^{-1}$, where dec is decade. The extent and area of the perennial ice cover, estimated from summer minimum values, have been declining at a much faster rate of $-6.7 \pm 2.4\%\ \mathrm{dec}^{-1}$ and $-8.3 \pm 2.4\%\ \mathrm{dec}^{-1}$, respectively, while the surface ice temperature has been increasing at $0.9 \pm 0.6\ \mathrm{K\ dec}^{-1}$. This unusual rate of decline is accompanied by a very variable summer ice cover in the 1990s compared to the 1980s, suggesting increases in the fraction of the relatively thin second-year, and hence a thinning in the perennial, ice cover during the last two decades. Yearly anomaly maps show that the ice-concentration anomalies are predominantly positive in the 1980s and negative in the 1990s, while surface temperature anomalies were mainly negative in the 1980s and positive in the 1990s. The yearly ice-concentration and surface temperature anomalies are highly correlated, indicating a strong link especially in the seasonal region and around the periphery of the perennial ice cover. The surface temperature anomalies also reveal the spatial scope of each warming (or cooling) phenomenon that usually extends beyond the boundaries of the sea-ice cover.

INTRODUCTION

The Arctic region is of particular interest because it is expected to provide early signals associated with a potential change in climate (Budyko, 1966; Manabe and others, 1992; Alley, 1995). Because of observed global warming, especially in the second half of the 1990s (Jones and others, 1999), it is important to know how such increases in temperature are reflected in the Arctic. Recent reports show that the sea-ice cover has been retreating by about $-3\%\ \mathrm{dec}^{-1}$ (Bjørgo and others, 1997; Parkinson and others, 1999), while submarine sonar data show a thinning by >1 m in deep-water portions of the Arctic (Rothrock and others, 1999; Wadhams and Davis, 2000) over a period of 4 dec, where dec is decade. The Arctic climate system is, however, a very complex system affected by periodic atmospheric phenomena, like the North Atlantic and Arctic Oscillations (Mysak, 1999), and unexpected changes in ice-cover dynamics. Accurate interpretation of observed Arctic changes thus requires a better understanding of Arctic processes.

The key objective of this study is to make simultaneous use of satellite sea-ice concentration and surface temperature data to gain insight into the changing Arctic climate. Co-registered datasets of these two geophysical variables are examined to obtain a better understanding of how the various components of the climate system interact and how they act in concert to influence the system. Previous studies on the variability and trends of the Arctic sea-ice cover have been carried out using solely satellite passive-microwave data or submarine sonar data. In this study, trends and spatial changes in the ice cover are analyzed in conjunction with trends and changes in surface temperatures. Anomalies in ice concentration and surface temperatures are examined on a year-to-year basis, and relationships between these two variables are evaluated. The results are also used to gain insight into the observed changes in the Arctic, interpret trends in the total ice cover and its surface temperature, and better understand the status of the perennial sea-ice cover.

VARIABILITY AND TREND OF THE SEA-ICE COVER

Although a slightly longer time series for sea-ice cover is available, the time period used in this study is 1981–99 since this is the period for which coincident and continuous infrared and passive-microwave satellite data are available. The procedure for deriving ice concentration from satellite passive-microwave data has been described before (Comiso and others, 1997) and will not be repeated here. The error associated with the ice-concentration data is about 5–15% under dry surface conditions, and increases when the surface becomes wet as the snow melts in spring and when melt ponds are formed over ice floes in the summer. In this study, the ice concentrations are derived using the Bootstrap algorithm as described in Comiso and others (1997). The values and trends may therefore be slightly different from those reported elsewhere (Bjørgo and others 1997; Parkinson and others, 1999) even for identical periods.

Ice-concentration maps are used to derive monthly ice extent, actual ice area and average ice concentrations within the pack, as done previously (Comiso and others, 1997; Parkinson and others, 1999). These are in turn used to calculate anomalies in monthly ice extent, actual ice area and ice concentration by subtracting the 19 year climatological averages created for each of the 12 months of the year. The anomalies in ice extent, ice area and ice concentration for each month from August 1981 through July 2000, which are also used for trend studies, are shown in Figure 1. Yearly averages were also calculated for analysis of the yearly variability and associated trend. The yearly averaging was done from August of one year to July the following year to be able to compare yearly differences between different ice seasons, instead of different annual averages that would extend from the middle of one ice season to the middle of another.

The plot of ice-extent anomalies (Fig. 1a) shows significant variability, with a standard deviation of 0.33×10^6 km^2. Simple linear regression of the data yielded a trend of $-246\,000 \pm 40\,000$ km^2 dec^{-1}, or -2.04 ± 0.33% dec^{-1}. This is significantly less than the -2.8% dec^{-1} reported by Parkinson and others (1999), but the latter was for a slightly different time period (i.e. 1978–96) and a different ice dataset was used (i.e. Team algorithm as described in Comiso and others, 1997), as indicated earlier. Anomalously low values occurred in 1989, 1990, 1993, 1995 and 1998, while an anomalously high value is apparent in 1996. The regression results from the yearly data yielded -2.04 ± 0.56% dec^{-1} the result of which is almost the same as the monthly anomaly data but with higher error.

The variability in the anomalies in actual ice area (Fig. 1b) is comparable to that of ice extent, with a standard deviation of 0.33×10^6 km^2. However, the trend in ice area is significantly larger at $-336\,000 \pm 36\,000$ km^2 dec^{-1}, or -3.11 ± 0.33% dec^{-1}. This is more in line with previous reports for the 1978–96 period. The yearly averages yielded similar trends but larger error at -3.12 ± 0.51% dec^{-1}.

The difference between the ice-extent and ice-area trends stems mainly from a net negative trend in ice concentration (Fig. 1c), estimated at -1.16 ± 0.12% dec^{-1}. The change in estimated ice concentration may not be entirely due to a change in true ice concentration since it could also be linked to a change in the areal coverage of melt ponding. To test this possibility, a similar analysis was conducted that excluded the summer months (June–August). The results yielded a trend in ice concentration of -1.09 ± 0.14% dec^{-1}, which is similar to that with the summer months included. This implies that the impact of changes in melt-ponded area on the trend results is not significant. However, excluding the summer months significantly reduced the trends in ice extent and area to -1.47 ± 0.14% dec^{-1} and -2.47 ± 0.37% dec^{-1}, respectively. This suggests that the trends in the ice cover during the summer, especially during minima, may be high as indicated later.

The distributions for the yearly average extent and area in Figure 1 exhibit a periodic cycle with a period of about 5 years. Such periodicity is intriguing in light of a possible correlation with many important processes, such as the Arctic Oscillation. The effect is not so apparent in the monthly anomalies. However, a detailed study of this phenomenon is beyond the scope of this paper.

DISCUSSION AND CONCLUSIONS

Co-registered satellite ice-concentration and surface-temperature data for the period 1981–2000 have been assembled and analyzed, and this study shows that simultaneous observation of the two parameters provides useful knowledge about the changing Arctic. Ice-concentration data provide physical characterization of sea-ice spatial distributions, while surface temperatures provide information about the thermal state of the ice surface. Each dataset provides independent evaluation of the changing state of the Arctic, but together they provide a more complete characterization.

A general assessment from the monthly and yearly data shows that ice extent has been declining at a rate of 2.3% dec^{-1} while surface temperature has increased by 0.4 K dec^{-1}. This rate of decline is smaller than the 2.8% dec^{-1} previously reported, but that value was for a different period (1978–96) and a different ice-concentration algorithm was utilized to generate the ice dataset.

The yearly anomalies in both ice concentration and temperature provide new insights into the changing Arctic ice environment. They provide year-to-year changes in good spatial detail of sea-ice distributions, and specific locations and magnitude of large positive and negative anomalies. The data show that positive anomalies in ice concentrations predominate in the 1980s, while the reverse is true in the 1990s. This indicates that the ice cover has been declining. Similarly, negative anomalies in surface temperatures were dominant in the 1980s, while positive anomalies were more frequent in the 1990s. This shows that while the ice cover is declining, the surface temperature is rising, indicating a close linkage of the two variables.

The yearly temperature-anomaly maps provide useful information that is not available from the sea-ice-cover data. These maps show that there are large anomalies in the Arctic that extend beyond the sea-ice margins. They allow quantification of the scope of these anomalies which are apparently driven by atmospheric patterns. The coherence of the spatial distribution of the anomalies of ice concentration and surface temperature is quite good, and quantitative analysis shows high negative correlation of the two variables, especially in the seasonal ice regions where the anomalies are abnormally high. It is also apparent that there were some years when the anomaly patterns were exceptionally high, such as 1998, which is regarded as the warmest year in the 20th century. High positive anomalies are indeed evident in the 1997/98 and 1998/99 ice seasons, but they are confined primarily to the Beaufort Sea and North America, while slight cooling occurred in Russia and the Kara Sea.

To better understand the current state of the Arctic ice cover, a good quantification of the variability of the perennial ice cover is required, derived from analysis of the extents and areas of the ice cover during summer minimum. Results show that the Arctic summer ice extent and area have been declining at a rate of -6.7 ± 2.4% dec^{-1} and -8.3 ± 2.4% dec^{-1}, respectively, while the average September surface temperature values increased by 0.9 ± 0.6 K dec^{-1}. The rate of decline in the perennial ice cover is more than twice the rate of decrease in total sea-ice cover. The rate of increase in surface temperature in September is also surprisingly high and more than double that for all seasons. These are significant results since they pertain to the perennial ice cover which is directly connected to the ice-thickness distribution. In addition, the minimum extent shows higher yearly fluctuations in the 1990s than in the 1980s. Even without a trend, such a phenomenon would cause a change in the overall composition of the different ice types, and favors increases in the fraction of the thinner, younger ice cover (e.g. second-year ice), compared with the older, thicker ice types. The large fluctuation in the areal coverage of the perennial ice cover may thus be accompanied by a decrease in ice thickness.